CITY TUNNEL OF THE CATSKILL AQUEDUCT[1]

By Walter E. Spear[2]

The peculiar topography of Manhattan Island, the relatively few streets in the older portions of New York City not already occupied by subways, pipes and ducts, and the swift tidal waters which separate the several boroughs of the city combined to make the problem of delivering the Catskill supply under full pressure to the great centers of population one of some difficulty. Until the problem was thoroughly investigated, the only way to provide for the distribution of the Catskill water appeared to be that of supplementing the existing conduits of the Croton system in the boroughs of The Bronx and Manhattan and constructing new pipe lines through the less congested streets in the borough of The Bronx from Hill View just north of the city line, to the borough of Queens, and thence to the boroughs of Brooklyn and Richmond. Except by laying a large number of independent trunk mains of large capacity to the lower end of Manhattan Island, a task physically almost impossible in the crowded streets, downtown New York could not secure the full advantages of increased pressure for fire protection and domestic consumption that the new system provides. Even if it had been possible to lay in the streets a large number of new pipe lines, the cost of such a system would have been about twice as much as the cost of the single conduit of the same capacity of more permanent construction that was finally adopted. Some type of pressure conduit of ample dimensions was required, because, even in The Bronx and upper Manhattan where the streets were comparatively free of subsurface structures, the ground was not at a sufficiently high elevation to permit the construction near the surface of a large masonry conduit like the Old Croton Aqueduct, because the Catskill supply when it reaches the city line is at an elevation of 295 feet above sea level or about 150 feet higher than the Croton supply.

[1] A paper read at the March, 1916, Meeting of the New York Section, illustrated by lantern slides.

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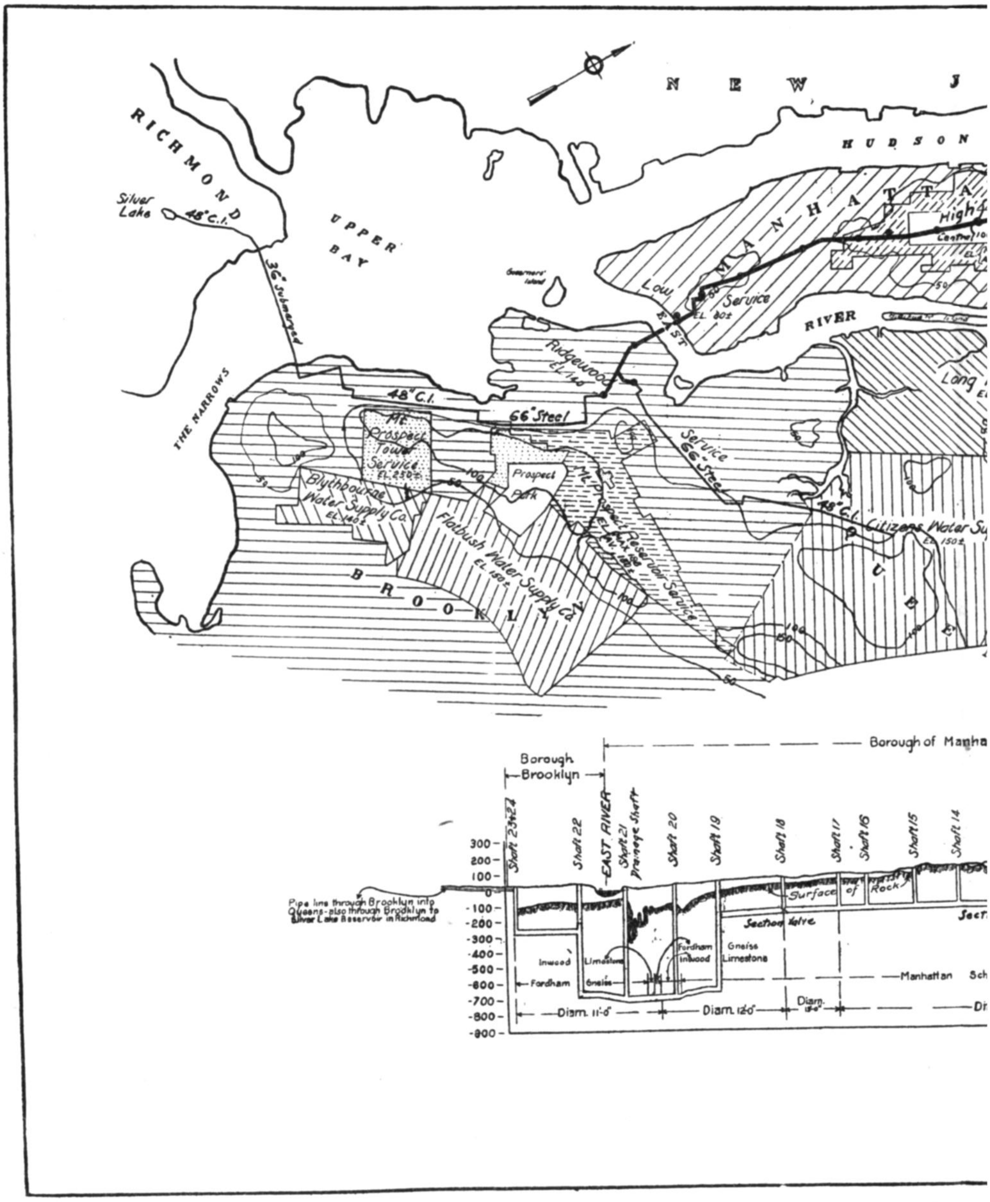


RICHMOND
Silver Lake
48" C.I.
36" Submerged
THE NARROWS
UPPER BAY
NEW J
HUDSON
MANHATTA
High
Low Service
EL. 80±
EAST RIVER
Ridgewood EL. 140
48" C.I.
66" Steel
Mt. Prospect Tower Service EL. 280±
Prospect Park
Blythbourne Water Supply Co. EL. 140±
Flatbush Water Supply Co. EL. 180±
Mt. Prospect Reservoir Service
Service 66" Steel
48" C.I.
Citizens Water Su
BROOKLYN
QUEE
Borough Brooklyn
Borough of Manha
Shaft 23 & 24
Shaft 22
EAST RIVER
Shaft 21 Drainage Shaft
Shaft 20
Shaft 19
Shaft 18
Shaft 17
Shaft 16
Shaft 15
Shaft 14
Pipe line through Brooklyn into Queens-also through Brooklyn to Silver Lake Reservoir in Richmond
Surface of Rock
Section Valve
Inwood Limestone
Fordham Gneiss
Fordham Gneiss
Inwood Limestone
Manhattan Sch
Diam. 11'-0"
Diam. 12'-0"
Diam.

PLATE I

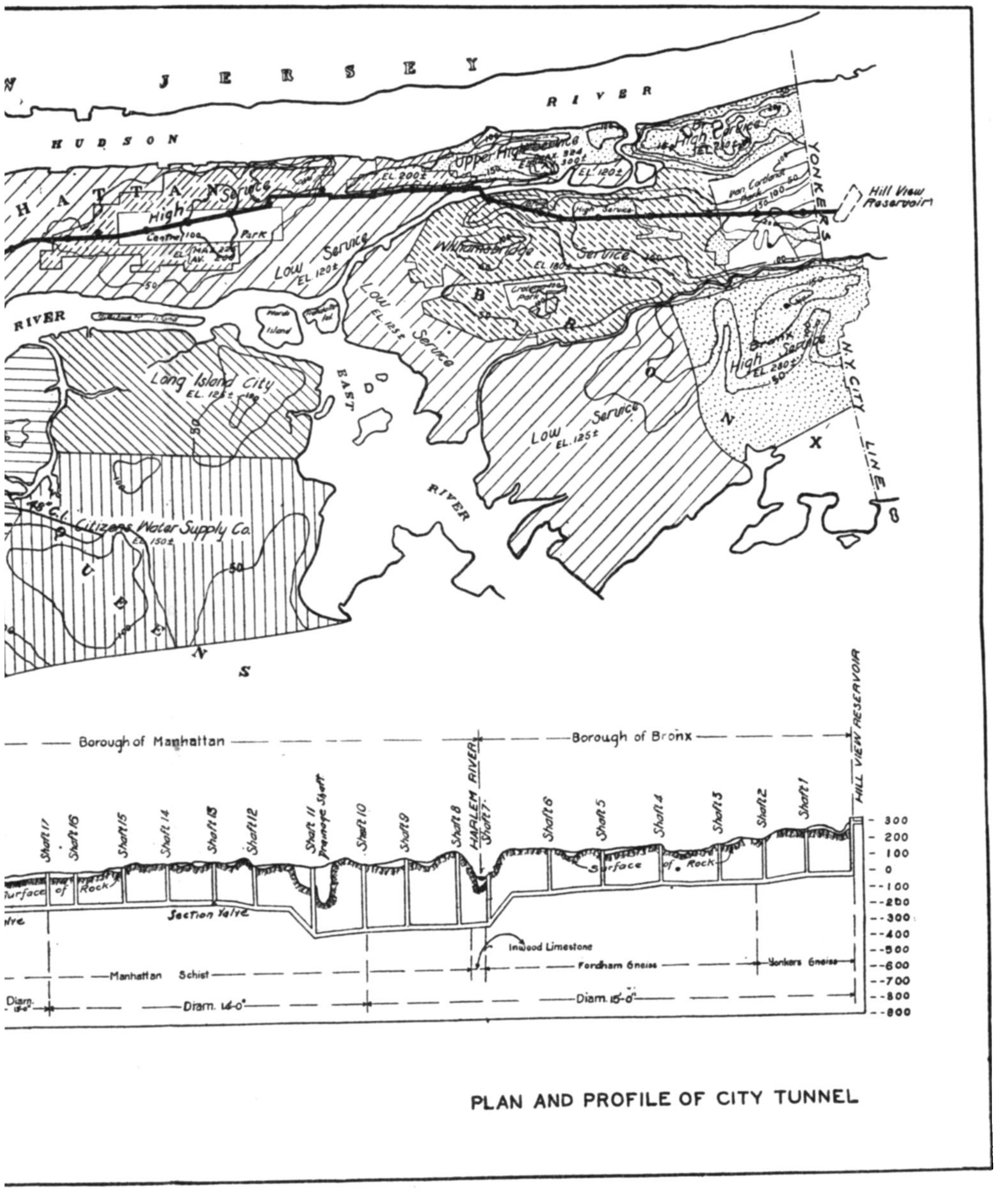

JERSEY
HUDSON
RIVER
Upper High Service
High Service
Hill View Reservoir
YONKERS
Low Service
Low Service EL. 125±
Williamsbridge Service
Long Island City EL. 125±
Citizens Water Supply Co. EL. 150±
EAST RIVER
Bronx High Service EL. 280±
N.Y. CITY LINE
Borough of Manhattan
Borough of Bronx
HARLEM RIVER
HILL VIEW RESERVOIR
Shaft 17
Shaft 16
Shaft 15
Shaft 14
Shaft 13
Shaft 12
Shaft 11 Drainage Shaft
Shaft 10
Shaft 9
Shaft 8
Shaft 7
Shaft 6
Shaft 5
Shaft 4
Shaft 3
Shaft 2
Shaft 1
Surface of Rock
Section Valve
Inwood Limestone
Manhattan Schist
Fordham Gneiss
Yonkers Gneiss
Diam. 14-0"
Diam. 15-0"
PLAN AND PROFILE OF CITY TUNNEL

PLATE I

While bed rock, which outcrops so frequently in The Bronx and upper Manhattan, would have offered much difficulty to the construction of a surface aqueduct or pipe line, it furnished a unique solution of the distribution problem, since it permitted the construction of a deep pressure tunnel in rock of the full capacity of the Catskill sources, from Hill View reservoir, through the boroughs of The Bronx and Manhattan to the downtown business district of Brooklyn, the tunnel serving as a great trunk distribution main, delivering water through frequent outlets at high pressure to the dense areas of population in these older parts of the city and also supplying, through pipe lines, the outlying districts in the boroughs of Brooklyn, Queens and Richmond.

As a result of surveys, borings and extended studies, covering a period of about two years, the location shown on Plate I, for the deep rock pressure tunnel, which is known as the City tunnel, was finally chosen. This location, which for its entire length is under streets and parks, follows in a general way the higher ground in the westerly portion of The Bronx and upper Manhattan, passes through Central Park, Sixth Avenue, Broadway and Fourth Avenue to the lower east side and thence across the East River to Brooklyn, where the rock floor becomes too low to carry this type of construction further. The city tunnel was driven at a depth of not less than 150 feet below the surface of sound rock, as determined by the outcrops and borings, in order to insure good driving, a minimum of water during construction and a tight waterway in service. This requirement placed the tunnel for over half its length in the Yonkers and Fordham gneiss formations of The Bronx and in the schist of Manhattan at a depth below the surface of about 200 feet. As indicated on the profile in Plate I, a somewhat greater depth, about 300 feet below sea level, was necessary from the Harlem River to the head of Central Park in order to secure sufficient cover in the Inwood limestone, beneath the Harlem River, and in the Manhattan schist at 123d Street. A still deeper depression, 700 feet below sea level, had to be made beneath the lower east side because of the great depth of decay there in the rock of the Fordham gneiss and Inwood limestone formations.

The city tunnel is 18 miles in length from Hill View reservoir to the terminal shafts in Brooklyn, and its finished diameter is 15 feet for the first 8 miles reducing from this size by successive decrements of 12 inches to 11 feet in Brooklyn. Of the 24 shafts

through which the tunnel was constructed, 22 were built as waterway shafts through which the Catskill supply could be delivered to the street mains. Shaft 1, a construction shaft, was plugged and Shaft 11 has no waterway. Two shafts, 11 and 21, both located at low points in the tunnel profile, were built as drainage shafts through which to unwater the tunnel for inspection and repairs. Beyond the terminal shafts in Brooklyn, trunk mains of 66-inch steel and 48-inch cast iron were laid through the streets to the boroughs of Queens and Richmond. In crossing the Narrows to Staten Island, two 36-inch flexible jointed cast-iron pipes were planned, one of which is now being laid.

One of the many unusual features of the city tunnel is the arrangement for cutting the tunnel into three sections by means of two section valves set in the main tunnel at the foot of Shafts 13 and 18. These section valves are of bronze, 66 inches in diameter, and each is operated by a hydraulic cylinder in the chamber at the top of the shaft.

SHAFT SINKING

With the exception of the six southerly shafts, Nos. 19 to 24 inclusive, the shafts in earth were excavated by ordinary open-cut methods. The excavations of the earth portions of shaft 19 to 24 presented unusual difficulties, on account of the greater depth to rock, and the proximity of elevated railways, subways and other subsurface structures. These shafts were sunk to rock by means of reinforced concrete caissons under compressed air. Except at Shaft 21, where 4 rectangular caissons were sunk to provide foundations for the superstructure, the caissons were from 18 to 24 feet in diameter with walls from 2 to 3 feet thick. The bottoms of the caissons were carried from 2 to 5 feet below the surface of sound rock in order to provide for a tight seal and permit the rock shafts to be excavated in free air without any inflow of water. A view of the caisson at Shaft 23 is shown on Plate II. At this shaft the rock is 140 feet below the surface and 95 feet of this depth is in water bearing sand. At the time this view was taken, about 40 feet of the caisson was below and 80 feet above the surface of the ground. An air pressure of 46 pounds per square inch was maintained for two weeks at this shaft during the excavation of the rock and the sealing of the caisson. From two to three months were consumed at Shafts 19 to 24 in sinking each of the caissons before excavation of the rock shaft could be begun.

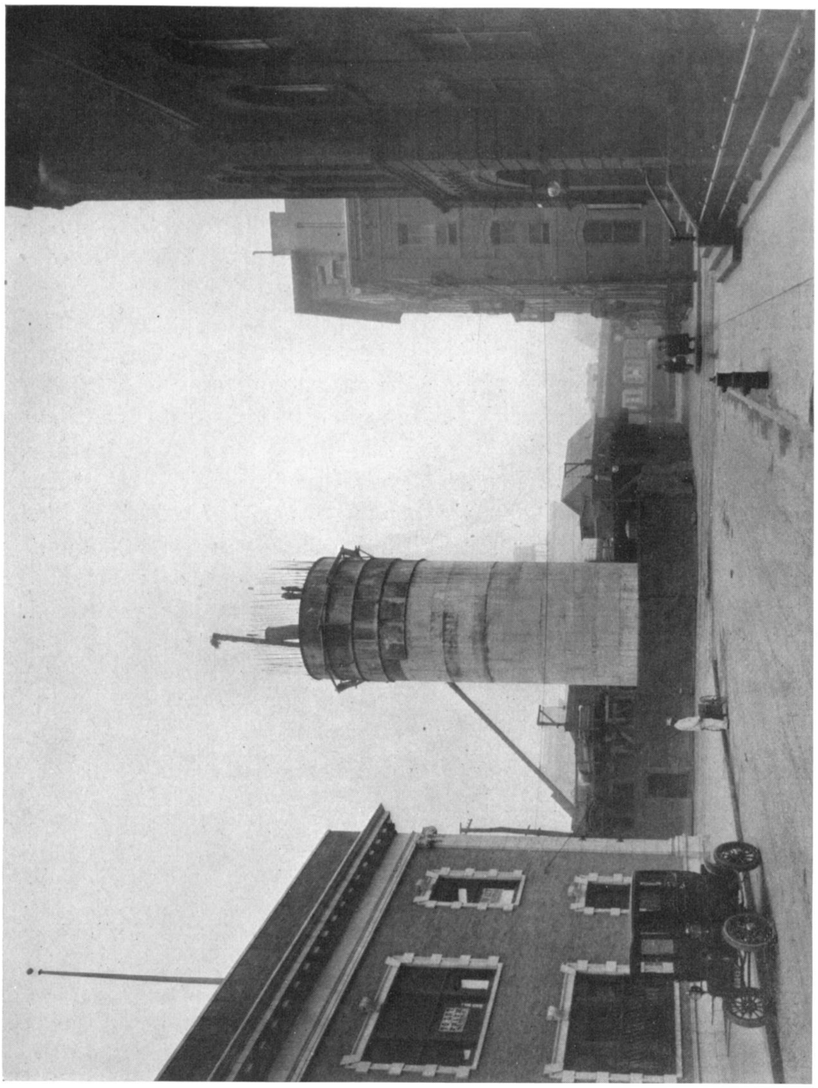


PLATE II

With the exception of Shafts 13 to 18, which were approximately rectangular in shape and were timbered as they were excavated, the shafts in rock were circular in shape, and were lined with concrete in stretches of about 100 feet as the excavation progressed. A finished diameter of 14 feet within this concrete lining was provided in all but three shafts which had diameters of 16 to 18 feet. From 25 to 30 feet of rock shaft were frequently excavated per week, but the average progress was less, on account of interruptions in sinking due to placing of concrete lining and because of delays occasioned by inflowing water. The average monthly progress for all shafts was 47 feet, and from 3 to 14 months were consumed at each shaft in sinking the shafts and placing the concrete lining.

All water encountered in the rock seams of the shafts was grouted off as far as possible in advance of the excavation, since it is difficult to find room for pumps to handle any considerable inflow without seriously interfering with the operations of drilling and mucking. At Shaft 4, near Jerome Park reservoir, a wide zone of broken and decayed rock was found near the bottom of the shaft which yielded a flow of 120 gallons per minute under a pressure of 70 pounds per square inch. The same crushed zone was later penetrated in the tunnel, where a flow of 400 gallons per minute was found. In sinking the shaft through this ground, many holes were drilled in the bottom, around the periphery of the shaft, to reach the water bearing seams, and grouting was carried on through these holes for several weeks. This grouting was partially successful in cutting off the flow, but it was not until the concrete lining had been placed and the shaft grouted, that the water was entirely cut off.

EXCAVATION OF TUNNEL

The preliminary borings indicated that no serious difficulties would be met in driving the tunnel. Some heavy ground requiring permanent steel roof support was encountered in several sections and in three stretches, one in the gneiss near Jerome Park reservoir, one in the limestone under Harlem River, and another in the granodiorite in Brooklyn, considerable water was met in the tunnel headings, but in no case was the flow so large as to greatly interfere with the excavation. The greatest flow, that in Brooklyn, was only 600 gallons per minute, and as soon as adequate pump-

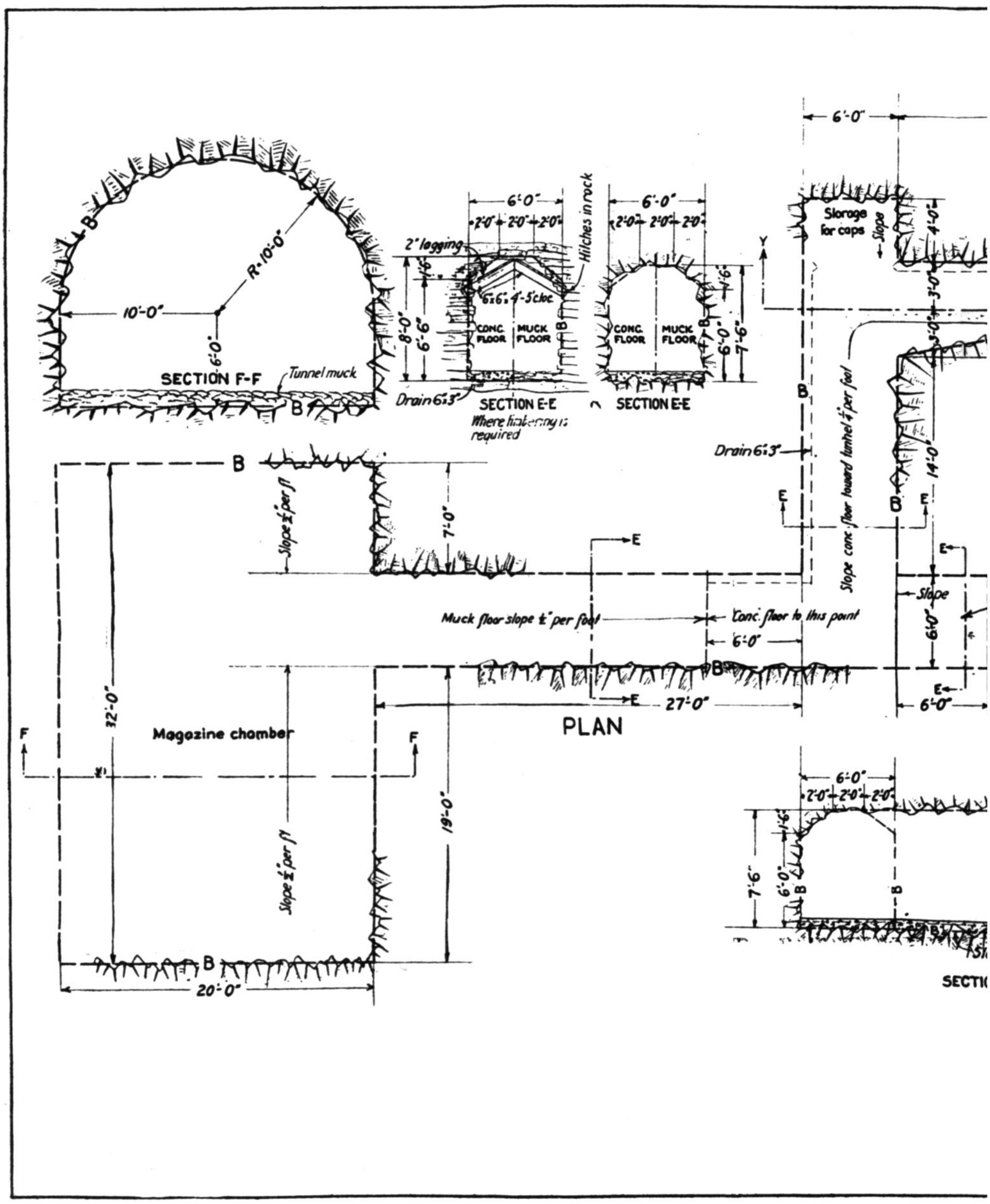
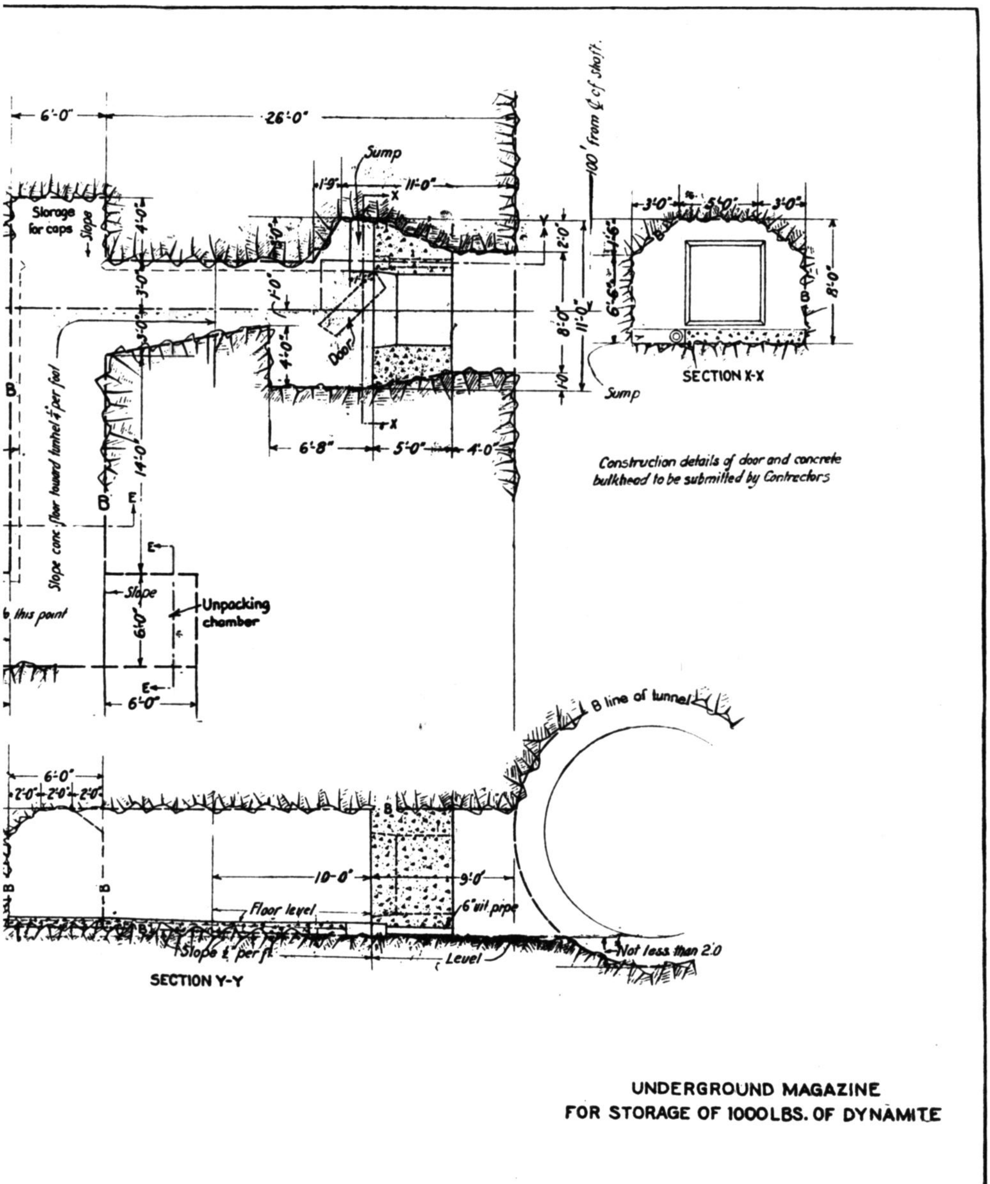

SECTION F-F
R-10'-0"
10'-0"
6'-0"
Tunnel muck
2" lagging
Hitches in rock
6'-0"
2'-0" 2'-0" 2'-0"
6x6, 4'-5" c.to c.
CONC. FLOOR
MUCK FLOOR
8'-0"
6'-6"
1'-6"
Drain 6x3"
SECTION E-E
Where timbering is required
SECTION E-E
7'-6"
Storage for caps
Slope
4'-0"
3'-0"
Drain 6x3"
Slope conc. floor toward tunnel 1/8" per foot
14'-0"
Slope 1/8" per ft
7'-0"
Muck floor slope 1/8" per foot
Conc. floor to this point
27'-0"
PLAN
Magazine chamber
32'-0"
19'-0"
20'-0"
SECTI

PLATE V



6'-0"
26'-0"
100' from ℄ of Shaft
Sump
1'-9"
11'-0"
X
Storage for caps
Slope
4'-0"
3'-0"
2'-0"
8'-0"
11'-0"
1'-0"
Door
4'-0"
14'-0"
6'-8"
5'-0"
4'-0"
Slope conc. floor toward tunnel ¼" per foot
this point
B
E
Slope
Unpacking chamber
6'-0"
3'-0"
5'-0"
3'-0"
8'-0"
6'-6"
1'-6"
SECTION X-X
Sump
Construction details of door and concrete bulkhead to be submitted by Contractors
B line of tunnel
2'-0"
10'-0"
9'-0"
Floor level
6" vit. pipe
Slope ⅛" per ft.
Level
Not less than 2'0
SECTION Y-Y
UNDERGROUND MAGAZINE
FOR STORAGE OF 1000 LBS. OF DYNAMITE

PLATE V

capacity was provided, the excavation was advanced with little delay. In this stretch grouting of the water bearing seams in advance of the driving was attempted, but without success, and the water was only cut off, as elsewhere, after the concrete lining of the tunnel had been placed and grouted.

The excavation of the tunnel, from the standpoint of cost and length of time required, was the largest item of the work, and the driving was prosecuted with the maximum of speed consistent with economy. The conditions in the city imposed on the contractors certain restrictions not generally encountered in work of this character. To avoid the noise and dirt incident to the use of steam, the contracts provided that as far as practicable electric power be used for all purposes. The regulations of the local authorities with regard to time of blasting required careful planning of the work until, as the headings were driven some distance from the shaft, more freedom in this respect was permitted.

Except for a short stretch excavated by the bottom heading method, the top heading and bench method, common in this country, was used in driving the tunnel. This method is shown on Plate IV. For the first year of the work 60 per cent Forcite was used, but for most of the rock excavation in the tunnel, the low freezing gelatine of the same strength was employed. This required no thawing and was therefore safer and more satisfactory. From 10 to 18 months were required to complete the tunnel excavation at each shaft. The best monthly progress made was 371 feet in one heading, and 652 feet in two headings, both in limestone, at Shaft 20. The average progress in one heading for the entire tunnel was 175 feet per month.

One of the important problems in connection with the driving of the tunnel was that of storing the large quantity of explosives necessary to carry on the work at the rate required under the contracts. The storage of 1000 pounds of dynamite at the top of each shaft in the built up portions of the city presented a serious problem to those responsible for the conduct of the work. After some study and investigation the underground magazine shown on Plate V was adopted. The magazine chamber in which the explosives were to be stored was excavated at the end of a tortuous drift, driven laterally from the main tunnel at a point distant about 100 feet from the foot of the shaft. A heavy door of steel beams and

timber was hung in such a position as to quickly close in the event of an accidental explosion in the magazine.

A cross section of the standard 15 foot tunnel in unsupported ground is shown on Plate III, this section being typical of the other sizes. The quantity of excavation and concrete for this type of tunnel is given below, the quantities being computed to the "B

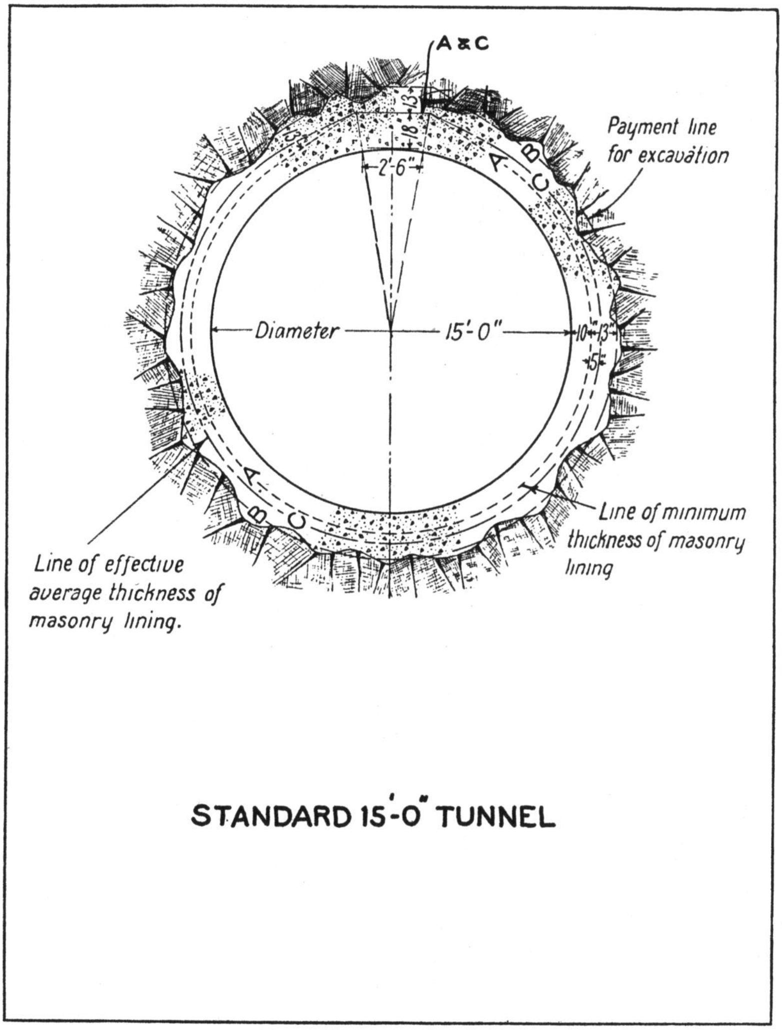
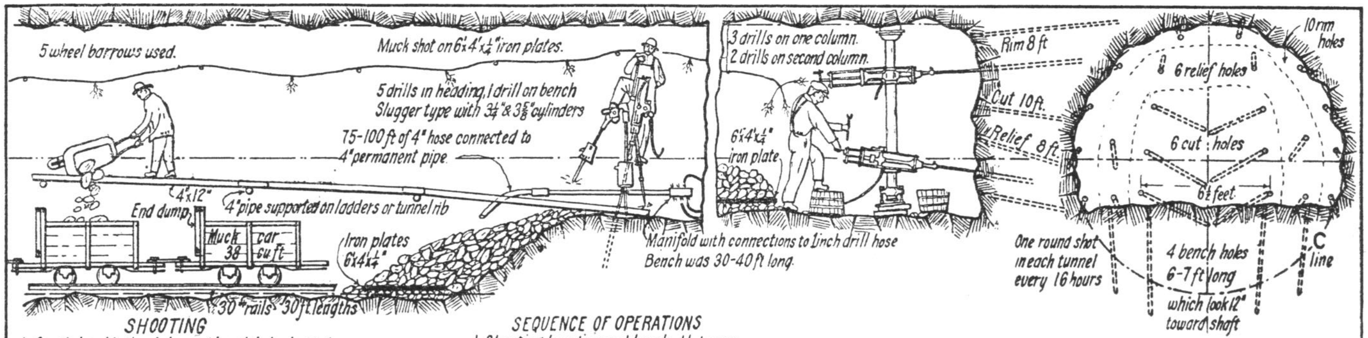


PLATE III



SHOOTING

1. 6 cut holes, 4 bottom holes and bench holes loaded.
2. Then 6 cut holes shot, rock falling clear of heading in large chunks.
3. Then 6 relief holes, remaining, loaded or all remaining holes loaded
4. 8 relief holes shot, rock falling down and a part backward.
5. 10 rim holes shot, rock falling down, very little backward.
Bench usually shot with cut round of heading.

SEQUENCE OF OPERATIONS

1. Shooting heading and bench - 1½ hours
2. Delay on account of smoke - ½ hour
3. Clearing out heading - 4 hours.
4. Setting up columns and drills - 2 hours
5. Drilling and mucking - 8 hours

SKETCH SHOWING TYPICAL METHOD OF EXCAVATION IN TUNNEL

PLATE IV

line" or payment line, corresponding to a distance of 10 inches to the "A line" which line defines the minimum thickness of concrete lining.

FINISHED DIAMETER OF TUNNEL	QUANTITIES PER LINEAR FOOT OF TUNNEL	
	Excavation	Concrete
feet	*cubic yards*	*cubic yards*
15	10.4912	3.9462
14	9.4268	3.7254
13	8.4212	3.5051
12	7.4016	3.2128
11	6.5109	2.9912

Under the provisions of the specifications, no point of rock was allowed to project within the "A" line shown on Plate III and no considerable area was permitted within the "C" line. On account of the alignment, the tunnel was driven very nearly parallel with the strike of the rock and some of the ground broke irregularly and wide, so that the actual excavation was on the average in all stretches of the tunnel in excess of the "B line," to which payment was made for both excavation and concrete, and thus giving an average thickness of concrete lining a little more than 23 inches.

In the 93,888 feet of tunnel within the city limits 6654 feet or 7.1 per cent was permanently supported with steel bents which were concreted into the lining. The amount of water encountered in the tunnel when first excavated aggregated 2436 gallons per minute but this amount gradually diminished as headings were advanced, and when the tunnel was finally lined and grouted, the total inward leakage was reduced to 130 gallons per minute.

TUNNEL LINING

The concrete lining was placed in three operations. The first step was to lay the invert in the bottom with radial joints and a top width varying from 4 to 6½ feet, the concrete being placed against wooden side forms. This work was carried on as a continuous operation and from 600 to 1500 feet were laid each week from one plant. After the invert was completed for a given stretch, the concrete in the sidewalls was placed, and then the arch. For this purpose collapsible steel forms of the Blaw type mounted on carriages running on

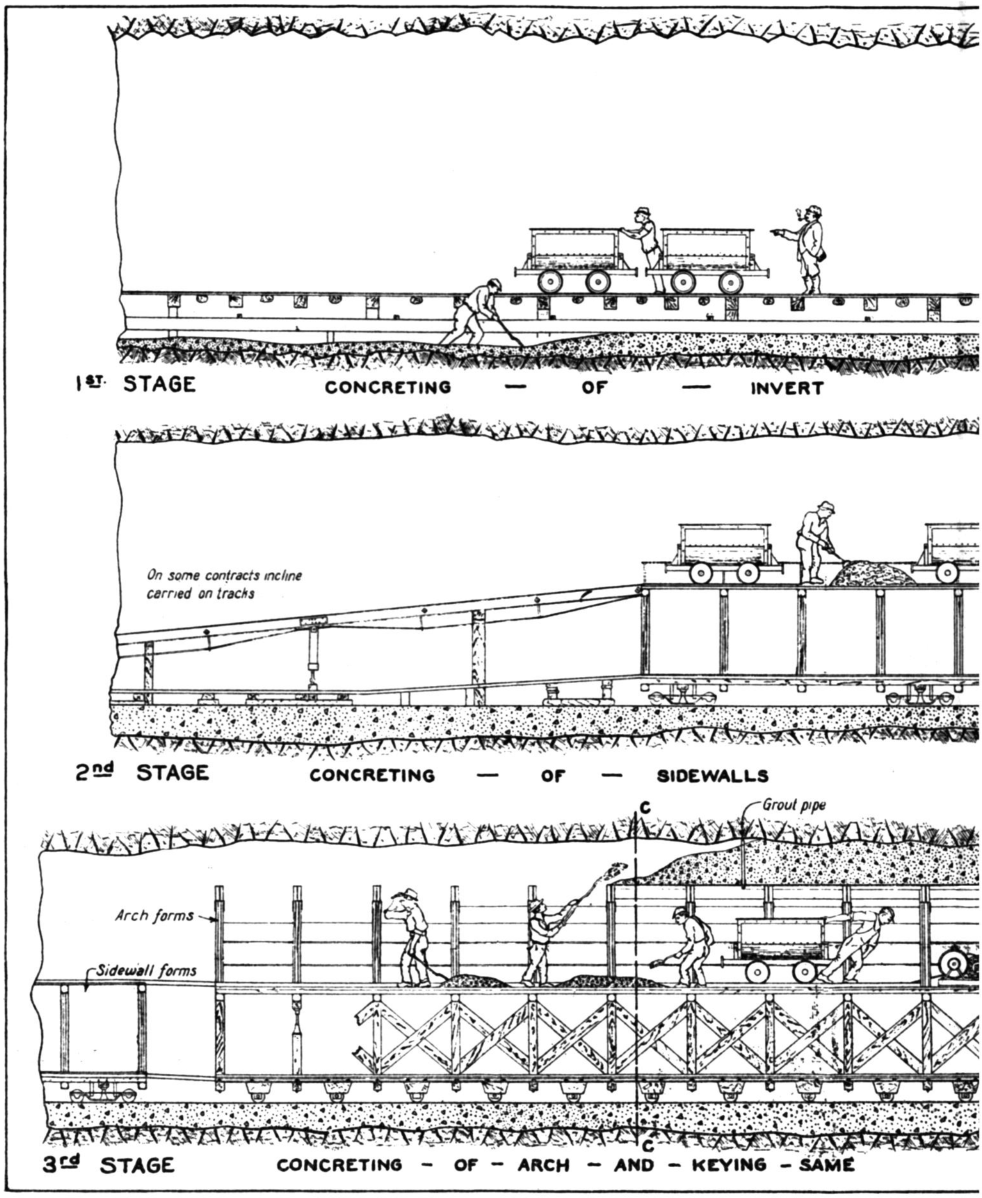

1st. STAGE
CONCRETING — OF — INVERT
On some contracts incline carried on tracks
2nd STAGE
CONCRETING — OF — SIDEWALLS
C
Grout pipe
Arch forms
Sidewall forms
C
3rd STAGE
CONCRETING - OF - ARCH - AND - KEYING - SAME

PLATE VI

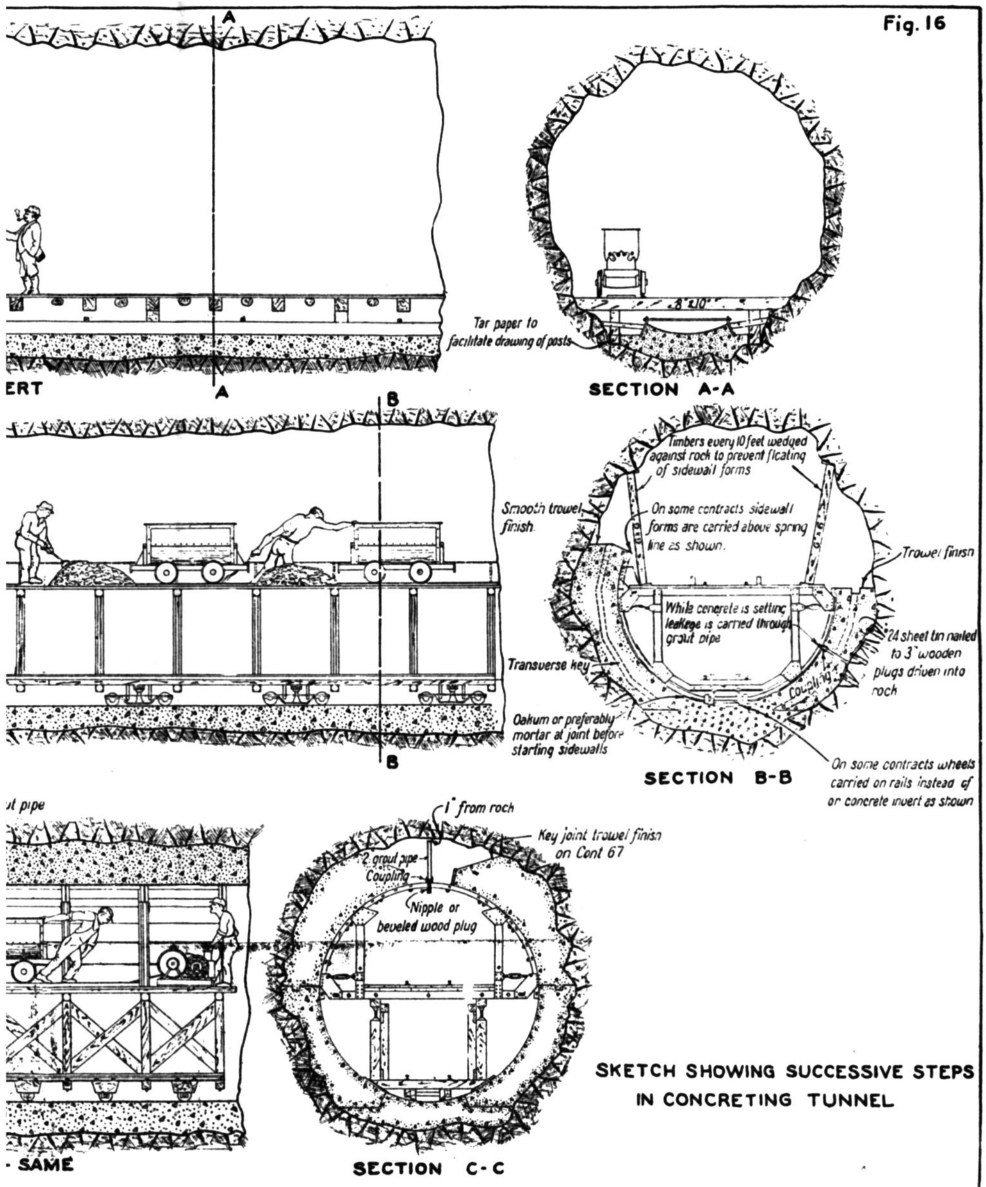


Fig. 16
A
A
ERT
Tar paper to
facilitate drawing of posts
SECTION A-A
B
B
Timbers every 10 feet wedged against rock to prevent floating of sidewall forms
Smooth trowel finish
On some contracts sidewall forms are carried above spring line as shown.
Trowel finish
While concrete is setting leakage is carried through grout pipe
24 sheet tin nailed to 3" wooden plugs driven into rock
Transverse key
Coupling
Oakum or preferably mortar at joint before starting sidewalls
SECTION B-B
On some contracts wheels carried on rails instead of on concrete invert as shown
1" from rock
Key joint trowel finish on Cont 67
2 grout pipe
Coupling
Nipple or beveled wood plug
SAME
SECTION C-C
SKETCH SHOWING SUCCESSIVE STEPS
IN CONCRETING TUNNEL

PLATE VI

the completed invert were used. For concreting the sidewall and arch, the forms were "trailed," that is, a length of sidewall form and an equal length of arch form were set up usually from 1 to 5 feet apart, the arch form trailing behind the sidewall form, as shown on Plate VI. The cars containing the concrete, in trains of 4 or 5 cars, were delivered to the foot of the incline, hauled up this incline by means of an electric hoist to the working platform set on the forms at approximately the level of the springing line and dumped, after which the concrete was shoveled by hand behind the forms.

The forms were usually from 60 to 100 feet in length; on one section, however, a set of sidewall and arch forms, each 150 feet long, was used. The shorter arch forms were keyed working continuously from one end, while with the longer forms, keying was started from two or three points and closures were made by means of a wooden box. Except for a somewhat drier mixture in the key of the arch, a wet plastic mix of $1:1\frac{1}{2}:3$ concrete was used throughout for the lining of the city tunnel. Some cracking developed in the sidewalls and arch between the joints defining the end of the day's work, but in very few instances did these cracks show any perceptible leakage.

In order to secure a dense, tight lining, provision was made to protect the concrete from inflowing water, while the concrete was being placed, by setting drip pans of galvanized iron or sheet steel, the pans being secured by nailing them to wooden plugs set in holes drilled in the rock. The water collected in these pans and escaped freely into the tunnel through weepers of $1\frac{1}{2}$-inch or 2-inch steel pipes, embedded in the concrete and extended through holes cut in the steel forms. The spaces between the pans and rock were subsequently grouted through these weepers.

Except at Shafts 2 and 4, the concrete was mixed on the surface, lowered on the cages and hauled to the forms in cars of about 1 yard capacity. At each of Shafts 2 and 4, the mixer was placed in the tunnel at the bottom of the shaft, and was fed through a 12-inch wrought iron pipe from storage bins containing the aggregates located at the surface. The cement for a batch was mixed with a small quantity of water and discharged through the pipe and then the aggregates followed. Very good progress was made in concreting the tunnel, from 600 to 1450 feet of completed lining being placed monthly from a single concreting plant. The best record from one plant was made at Shaft 9, where 2394 feet of

sidewall and arch were placed in one month, equivalent to approximately 9500 cubic yards. From 4 to 10 months were spent in placing the lining from each plant.

GROUTING OF TUNNEL

In order to fill all voids over the tunnel arch and back of the lining, grout was forced under low pressure through pipes which were set in the arch at intervals of about 30 feet at the time the concrete was placed. The high vent pipes in the roof, as well as deep seated pipes tapping water-bearing seams were subsequently grouted under a pressure of 250 to 300 pounds per square inch. For low pressure work, a grout of 1 of cement to 1 of sand was generally used, while neat cement was used for high pressure grouting. Air-stirring grouting machines of the Caniff type were employed for grouting, the air pressure being raised for high pressure work by means of portable auxiliary air compressors or "boosters."

SHAFT CLOSURES AND EQUIPMENT

After completion of the concreting and grouting of the tunnel, the shaft closures were made and then the valve chambers were constructed just below the surface of the ground. In the upper portion of each waterway shaft, extending from the floor of the valve chamber down to a depth of at least 100 feet below the top of sound rock, one or two steel riveted pipes were placed and embedded in a concrete plug inside of the shaft lining. These vertical risers are lined with 4 inches of concrete to protect the steel and to make a smooth waterway, with a finished diameter of 4 feet, except that the larger shafts are provided with two 72-inch risers. These risers were each capped by a bronze tee or shaft cap, solidly anchored into the concrete of the shaft plug. This cap has two lateral outlets, to which either 30 or 48-inch bronze gate valves are connected. The bronze valves are for emergency use as valves of the ordinary bronze mounted cast iron pattern are installed next to the bronze gate valves for service operation. On bypass lines around the iron valves, 16-inch pressure regulating valves have been set, wherever water is to be supplied at pressure below the Catskill gradient. A view of one of the larger shaft caps and connecting valves taken in the chamber at Shaft 23 is shown on Plate

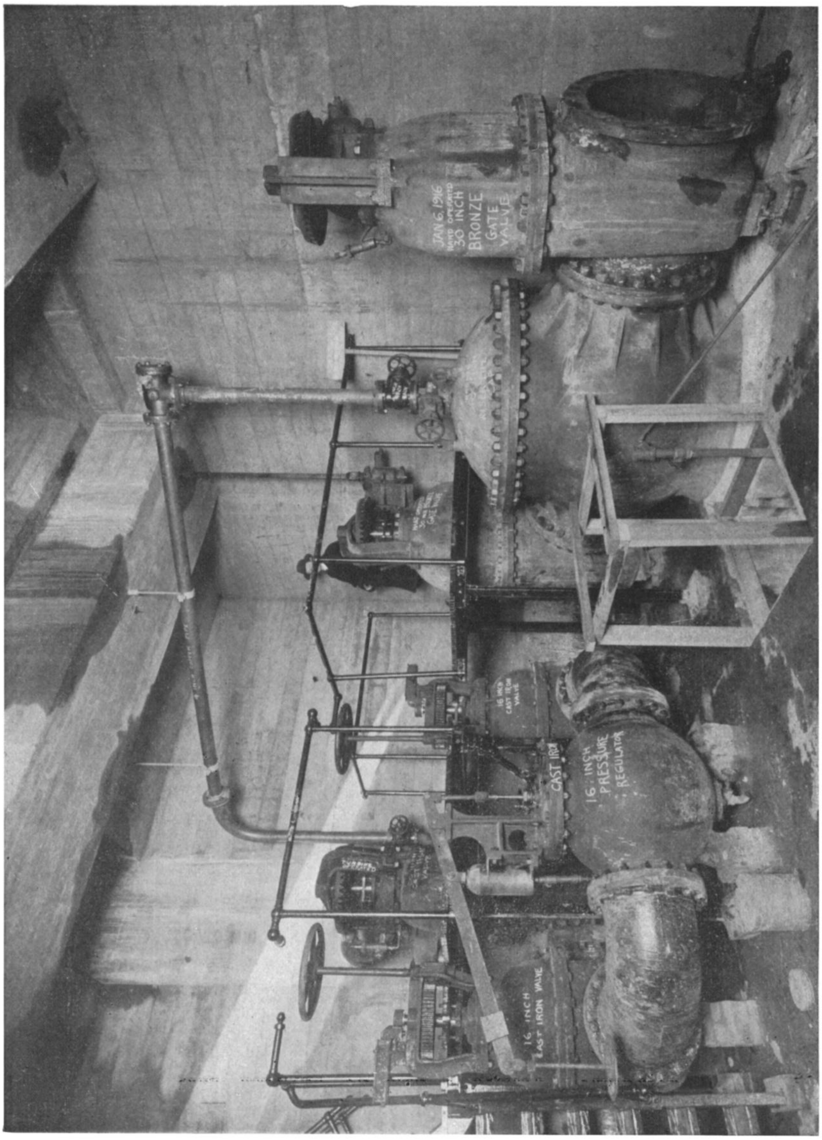

JAN 6 1916
30 INCH
BRONZE
GATE
VALVE
16 INCH
PRESSURE
REGULATOR
16 INCH CAST IRON VALVE

PLATE VII

VII. Venturi meters to measure the discharge in the connecting lines will also be placed in these chambers.

As an additional safeguard against the possible breaking of surface connections, a most interesting and unusual device was adopted to cut off the discharge through the shaft. A valve set at the bottom of each riser is designed to close automatically when the velocity in the riser exceeds a maximum for which the operating mechanism is set. The moving part of this riser valve, which in its exterior form resembles a needle valve, is a tight cylinder moving on a fixed piston, the cylinder communicating with the surface through a small pipe by which the operation of the valve is controlled.

TESTING OF TUNNEL

Upon the completion of contract work the city tunnel was subjected to hydrostatic tests under the full pressure corresponding to the level of the water in Hill View reservoir at elevation 295. The outward leakage under this maximum service pressure from the two northerly sections of the tunnel, 13½ miles in length between Hill View reservoir and Shaft 18 at 25th Street, on which the average unbalanced head was about 225 feet, was approximately 400 gallons per minute, or an average of about 30 gallons per minute per mile, after the full pressure had been maintained for several weeks. On the lower 4½ miles of tunnel, the hydrostatic test developed a somewhat higher rate of leakage, and the tunnel lining after unwatering showed slight cracking in a stretch of about 1000 feet where the pressure had apparently slightly compressed the rock. While the amount of leakage in this section of the tunnel would not at all have been considered serious outside of the city, it was deemed advisable to make the lining in the city as tight as possible, and a contract was accordingly awarded for lining with sheet copper the stretch affected.

A temporary supply from 20,000,000 to 50,000,000 gallons per day from the Catskill sources has been furnished to the borough of The Bronx since the first of the year and it is planned to put the entire tunnel into service with other portions of the Catskill Aqueduct before the close of 1916 when a supply of 250,000,000 gallons per day from Esopus Creek will be available. The introduction of the Catskill supply will permit the suspension of the expensive

pumping plants in the boroughs of Brooklyn, Queens and Richmond, largely cut down the present pumping in the boroughs of The Bronx and Manhattan and greatly improve the pressure in many sections of the city. The present gravity sources supplying Manhattan and The Bronx boroughs, namely the Croton, Bronx and Bryam supplies, will continue to furnish water for the low services and a portion of the higher services in these boroughs, but in other portions of the city the present pumped supplies will be temporarily abandoned and held in reserve for future needs.

COST

Data in regard to the cost of the city tunnel follow. The major contracts have been entirely completed, but superstructures have not yet been erected and some equipment remains to be placed, so that the figures for these items are not final but are substantially correct.

Preliminary Investigations:		
Borings, Contracts 38, 73, 98	$171,942	
Surveys and studies	189,357	$361,299
Real Estate:		
Awards for tunnel easement and shaft property	314,414	
Expenses of condemnation	35,904	350,318
Construction:		
Tunnel Contracts 63, 65, 66 and 67	$18,415,000	
Equipment contracts	880,000	
Superstructures	150,000	
Engineering	950,000	20,395,000
		$21,106,617

The unit costs of the several sizes of tunnel based on the estimated final quantities and the contract prices, and exclusive of preliminary work, real estate, superstructures and engineering, are shown in the following table:

Estimated cost of the city tunnel

DIAMETER OF TUNNEL	LENGTH OF TUNNEL	NUMBER OF SHAFTS		DEPTH OF SHAFTS			COST OF TUNNEL PER LINEAR FOOT	
		For construction only	For waterway, access and drainage	Minimum	Maximum	Total	Tunnel only	Total including shafts and equipment
feet	*feet*			*feet*	*feet*	*feet*		
15	38,926	1	8½*	218	477	2,910	$146	$195
14	26,247	0	7	220	447	1,954	151	202
13	4,554	0	1	204	224	214	146	182
12	9,080	0	2	204	749	1,005†	141	204
11	15,096	0	4½*	318	757	2,305†	139	249

* Where tunnel diameter changes, one-half cost of shaft is charged to each size tunnel.

† Lengths of tunnel and depths of shafts are according to original profile on which payment is based.